

Plume Impingement to the Lunar Surface: A Challenging Problem for DSMC

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The President's Vision for Space Exploration calls for the return of human exploration of the Moon. The plans are ambitious and call for the creation of a lunar outpost. Lunar Landers will therefore be required to land near predeployed hardware, and the dust storm created by the Lunar Lander's plume impingement to the lunar surface presents a hazard. Knowledge of the number density, size distribution, and velocity of the grains in the dust cloud entrained into the flow is needed to develop mitigation strategies.

An initial step to acquire such knowledge is simulating the associated plume impingement flow field. The following paper presents results from a loosely coupled continuum flow solver/Direct Simulation Monte Carlo (DSMC) technique for simulating the plume impingement of the Apollo Lunar module on the lunar surface such as presented in Fig. 1. These cases were chosen for initial study to allow for comparison with available Apollo video. The relatively high engine thrust and the desire to simulate interesting cases near touchdown result in flow that is nearly entirely continuum. The DSMC region of the flow field was simulated using NASA's DSMC Analysis Code (DAC) and must begin upstream of the impingement shock for the loosely coupled technique to succeed. It was therefore impossible to achieve mean free path resolution with a reasonable number of molecules (say 100 million) as is shown in Fig. 2. In order to mitigate accuracy and performance issues when using such large cells, advanced techniques such as collision limiting and nearest neighbor collisions were employed. The final paper will assess the benefits and shortcomings of such techniques. In addition, the effects of plume orientation, plume altitude, and lunar topography, such as craters, on the flow field, the surface pressure distribution, and the surface shear stress distribution are presented. (see Fig. 3).

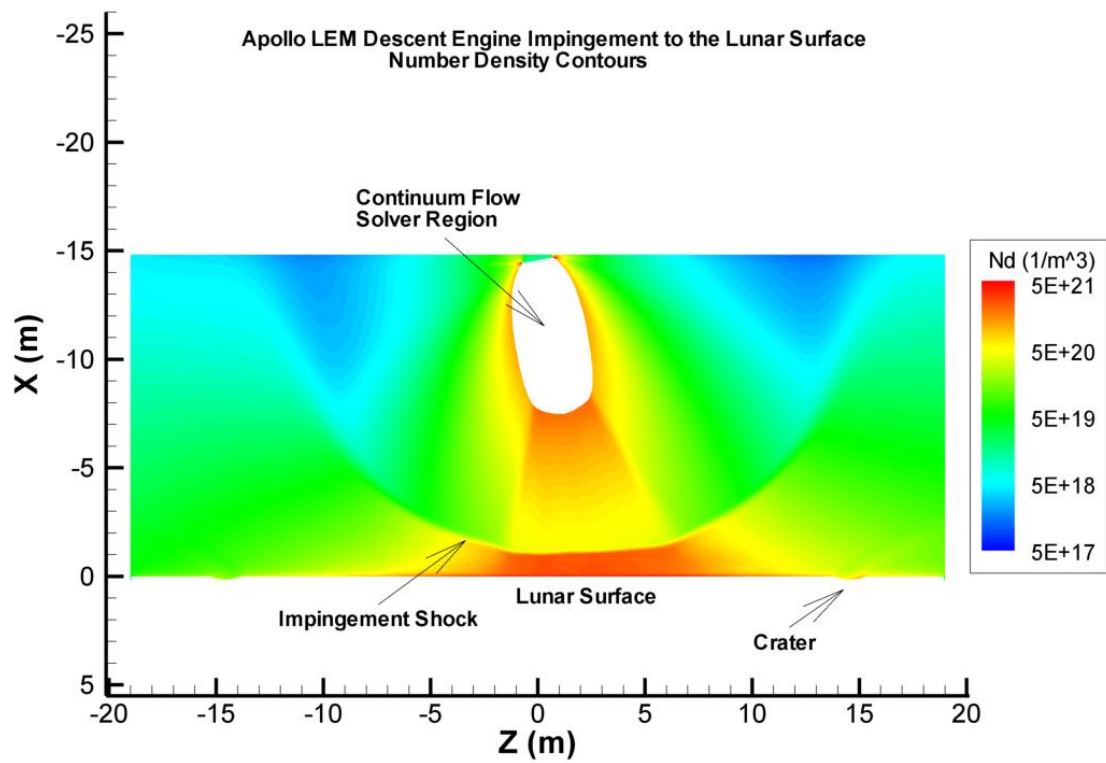


Fig. 1 Number Density Contours

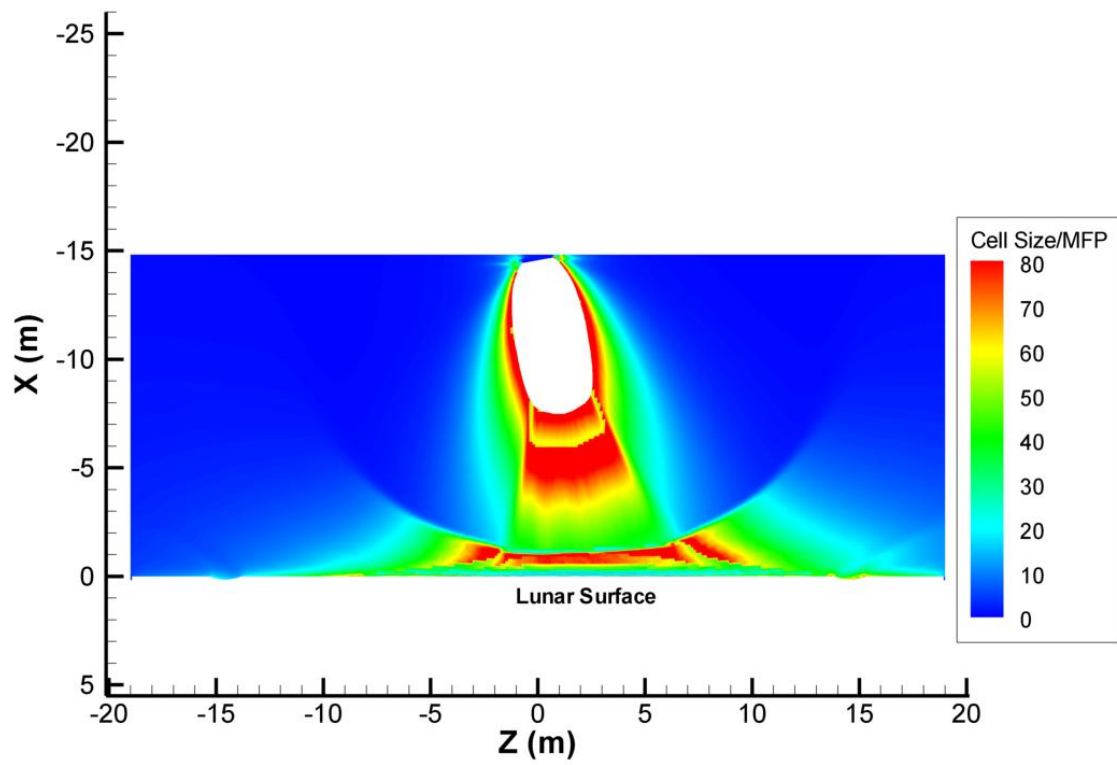


Fig. 2 Cell Resolution Contours

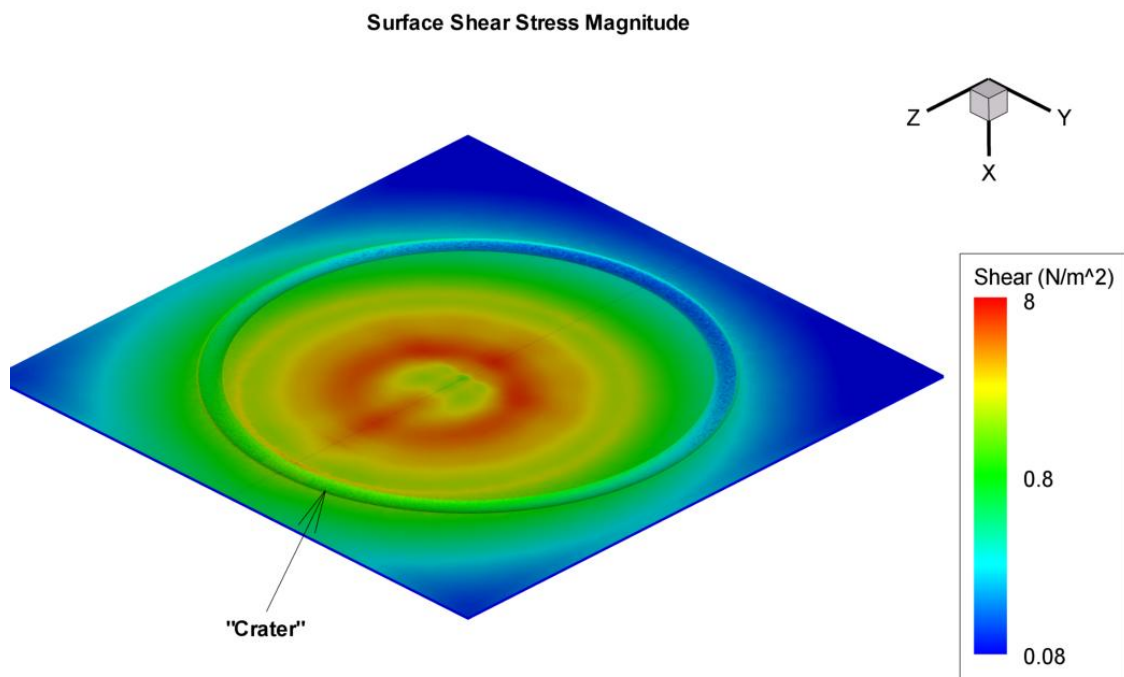


Fig. 3 Plume Impingement Shear Stress to Lunar Surface



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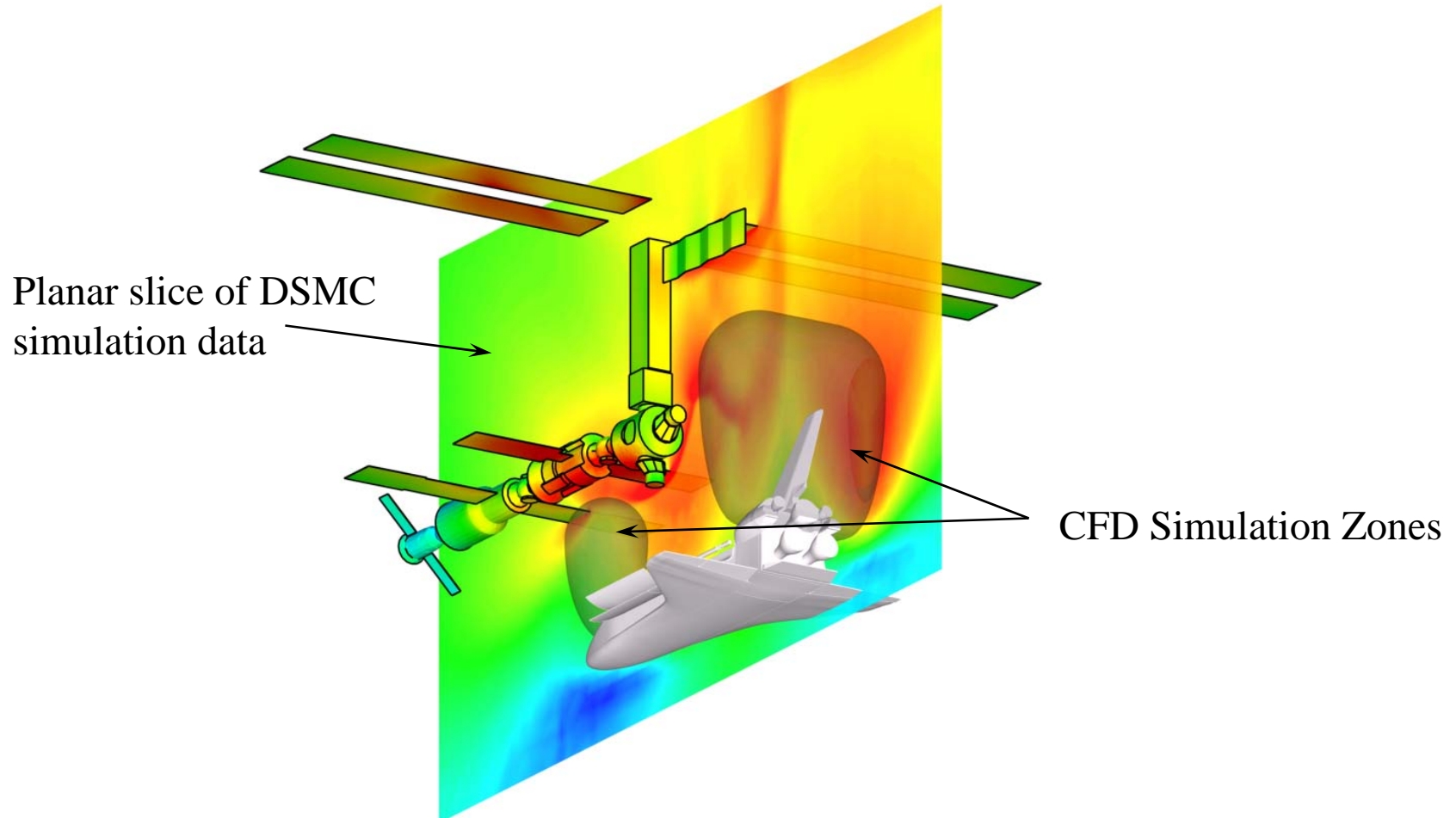
Background



- NASA's Vision for Space Exploration calls for a return of humans to the Moon.
- The required Lunar Lander will, like the Apollo LM, land on the Moon via a powered descent & have separate ascent and descent stages.
 - The resulting descent plume will impinge the lunar surface and create a dust/debris hazard for other lunar assets.
 - The ascent stage plume will impinge on the descent stage presenting a risk to any planned re-use of descent stage components.
- Understanding these plume impingement environments is necessary to quantify the risk and develop mitigation strategies for the Lunar Lander.
- NASA-JSC has had good success assessing plume impingement environments for on-orbit RCS plume impingement during Orbiter/ISS proximity operations.
 - Challenging problem due to the several orders of magnitude change in density as the flow expands from the RCS combustion chamber to vacuum conditions.
 - Requires a two phase approach.
 - Traditional computational fluid dynamics (CFD) for the higher density regions.
 - Direct Simulation Monte Carlo (DSMC) technique for lower density areas where CFD is no longer accurate.
 - Minimizes the difficulties associated with applying a vacuum boundary condition to CFD solvers.
 - One CFD nozzle/plume solution may be used for multiple DSMC plume impingement simulations



Example On-Orbit Plume Impingement Simulation



Norm-Z Plume Impingement on ISS Stage 4A



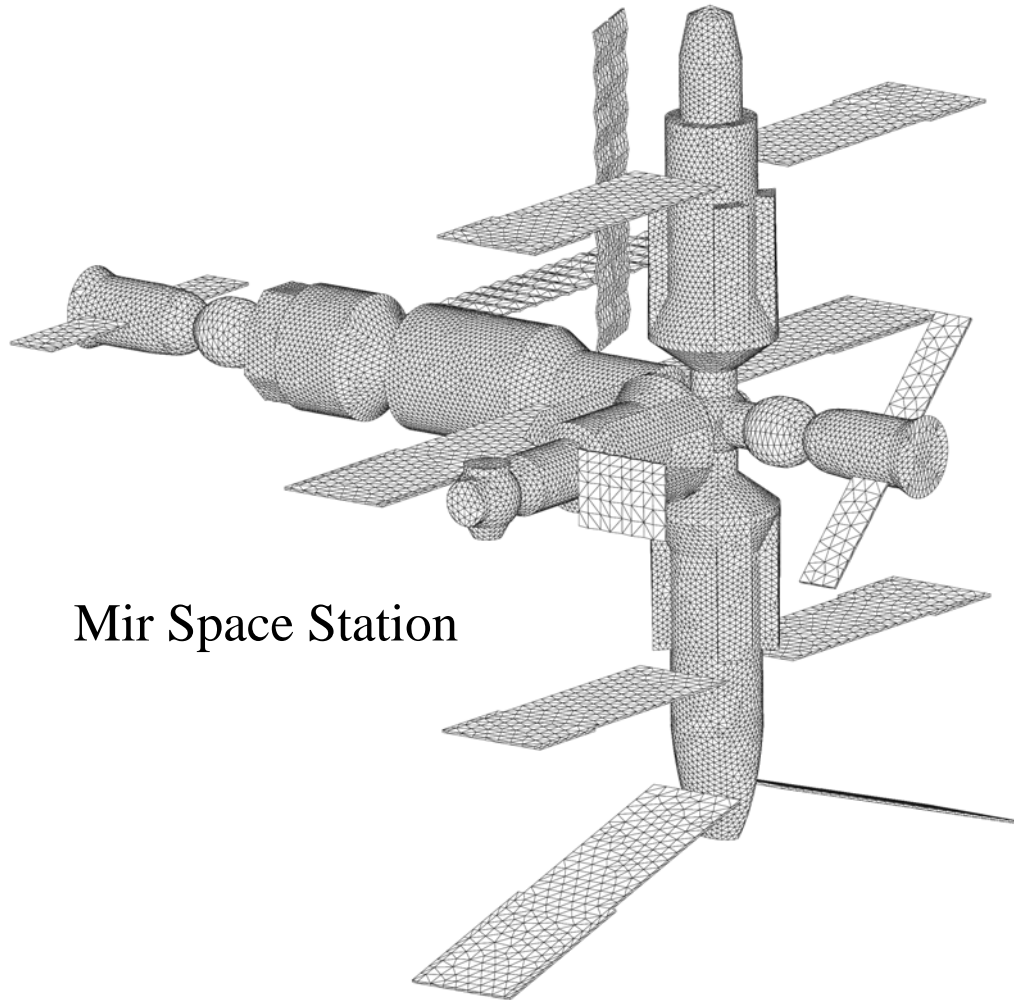
JSC DSMC Analysis Code (DAC97)



- Developed as a general purpose DSMC code, but with the plume impingement problem as a key capability.
 - Generalized surface with non-uniform inflow conditions (density, velocity, single temperature)
 - Allows a plume in flow boundary with conditions interpolated from a CFD simulation to be employed.
 - Assumes the in flow distributions are Maxwellian.
 - Advanced features to handle flows with large density gradients
 - Time step and simulated to real molecule ratio scaling.
 - Two level Cartesian mesh allows for refinement in areas with higher densities.
 - Scaling of real to simulated molecule ratio allows for nearly uniform number of simulated molecules per cell (goal ~10 for optimal performance and accuracy)
 - Nearest neighbor collision partner selection allows a slight relaxation of the mean free path cell size requirement
 - Other advanced features of note
 - Automated volume meshing (ease of use)
 - Massively parallel implementation with dynamic load balancing (allows simulations with 100's of millions of molecules)
 - Thermochemistry of Bird's G2 Code.
- Co-winner of 2002 NASA Software of Year Award



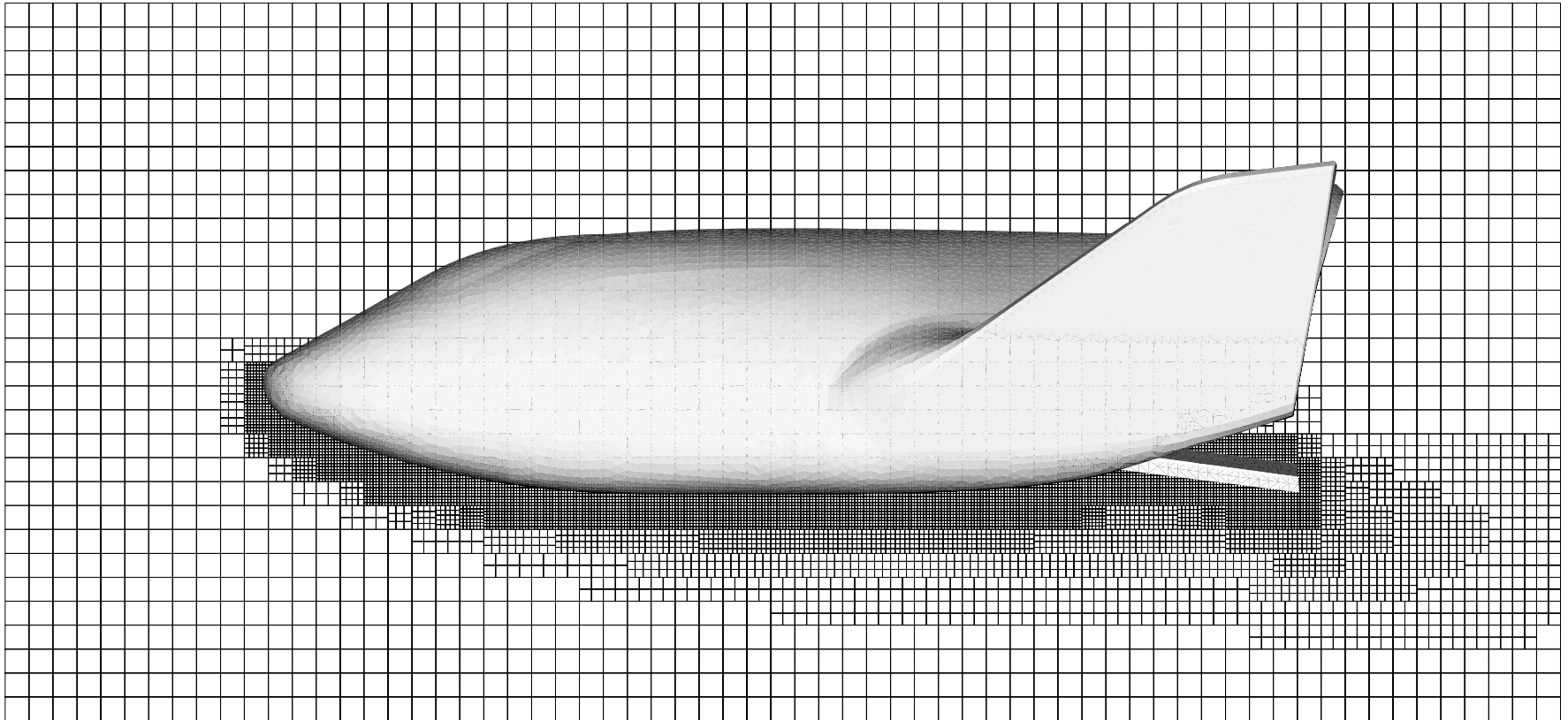
Typical DAC97 Surface Mesh



Mir Space Station



Typical DAC97 Surface Mesh Slice





DAC97 Features (continued)



- Surface meshes and volume mesh are completely decoupled
 - User required to generate surface mesh (triangulated)
 - Volume mesh resolution is not a function of surface mesh resolution
 - A single surface mesh may be used for adapted and unadapted problems
 - In other words, no need to regenerate the surface mesh when adapting the volume mesh
- Volume mesh adaptation
 - Default setting is to adapt to the local mean free path
 - Options to allow resolution goal to be greater or smaller than a mean free path
 - Different setting for cells near body and away from body
- DAC97 is a set of codes
 - stp: a utility code for working with surface meshes
 - predac/dpredac: volume meshing/adaptation code (scalar and parallel version)
 - dac/ddac: simulation code (scalar and parallel version)
 - slice/sprop/mkdb: Post processing codes for generating simulation plots



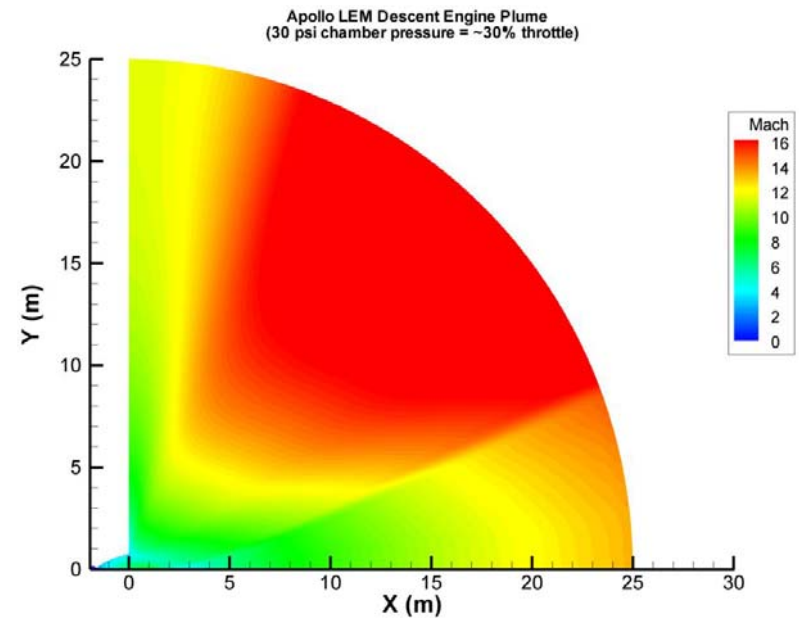
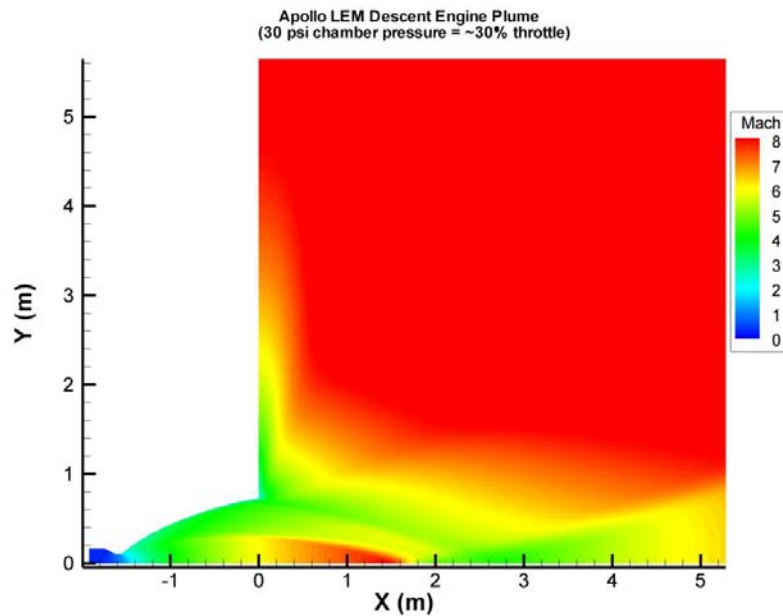
Plume Flow Simulations Performed for Lunar Architecture Team 2



- Performed 17 flow simulation cases to be used as the environment for forcing lunar dust motion.
 - Cases for Apollo LM descent engine allows comparisons to Apollo videos.
 - Required only a single CFD simulations of Apollo LEM descent plume.
 - Cases explored effects of lander height from surface, angle of engine to surface, crater size and location, and varying thrust.
 - Cases A1-A5 explored angle of engine to surface with an “torroidal crater”.
 - Case B explored normal shaped crater.
 - Cases C4-C5 explored crater locations and lander height
 - Cases D1-D5 explored variations in engine thrust
 - Case E explored crater size.



Apollo LM Nozzle/Plume Flow Field CFD Simulation





Impingement of Apollo LM Descent Plume on Lunar Surface – Density

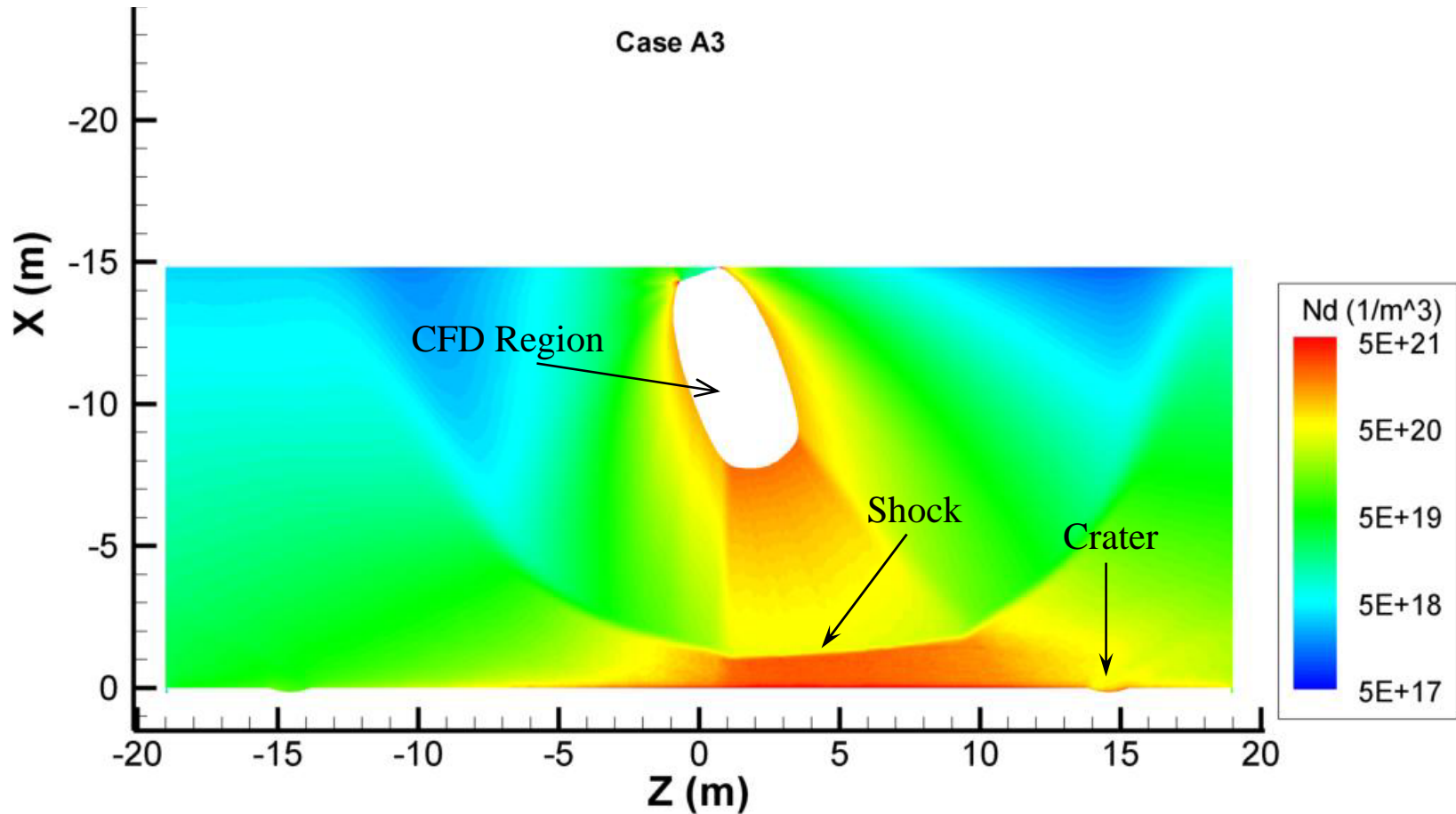
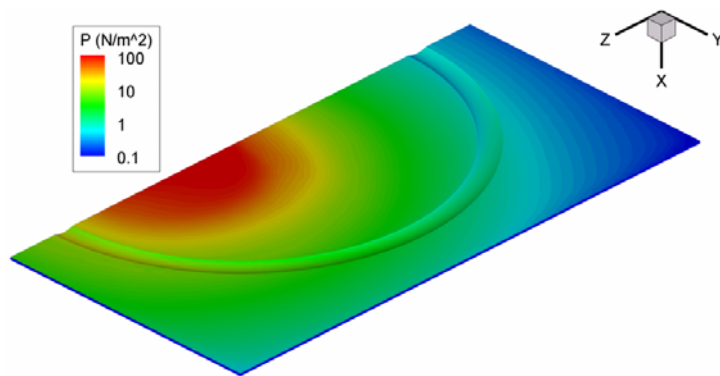




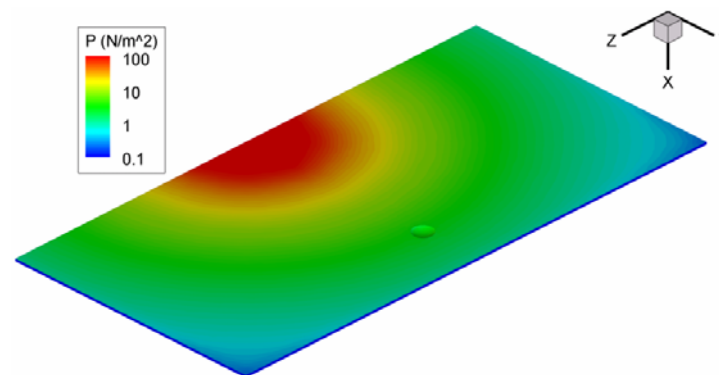
Illustration of different cases



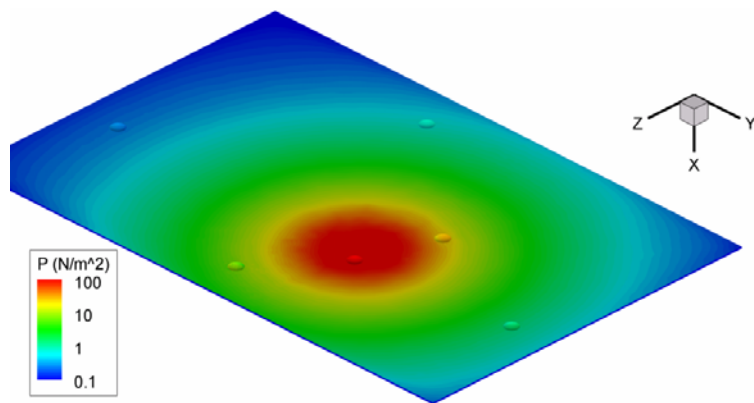
Case A3



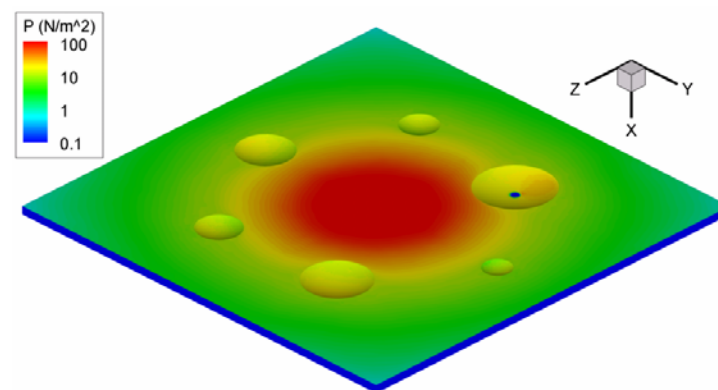
Case B



Case C5



Case E





Limitations of Current Technique



- The simulation must be able to be split cleanly into CFD and DSMC regions.
 - Interface between regions must be located where the flow is supersonic.
 - The loosely coupled approach provides no way for the flow in the DSMC region to affect the flow in the CFD region.
 - The cleanest approach is to place the interface upstream of any impingement shock waves.
 - However this may be where the flow is very continuum (i.e. the mean free path between molecules is small).
 - Traditional DSMC requires a simulation fidelity length scale on the order of a mean free path – hence simulation cost scales with the inverse of mean free path (to the third power for three dimensional simulations).
- Lunar plume impingement simulations are much more challenging than on-orbit RCS plume impingement.
 - Larger thrust = smaller mean free paths.
 - Most interest is at conditions near touch down = not much room between nozzle exit and surface impingement shock wave.
- Simulations of ascent stage plume on descent stage will be even more problematic due to the bounding case being when the ascent stage is in close proximity to the descent stage.



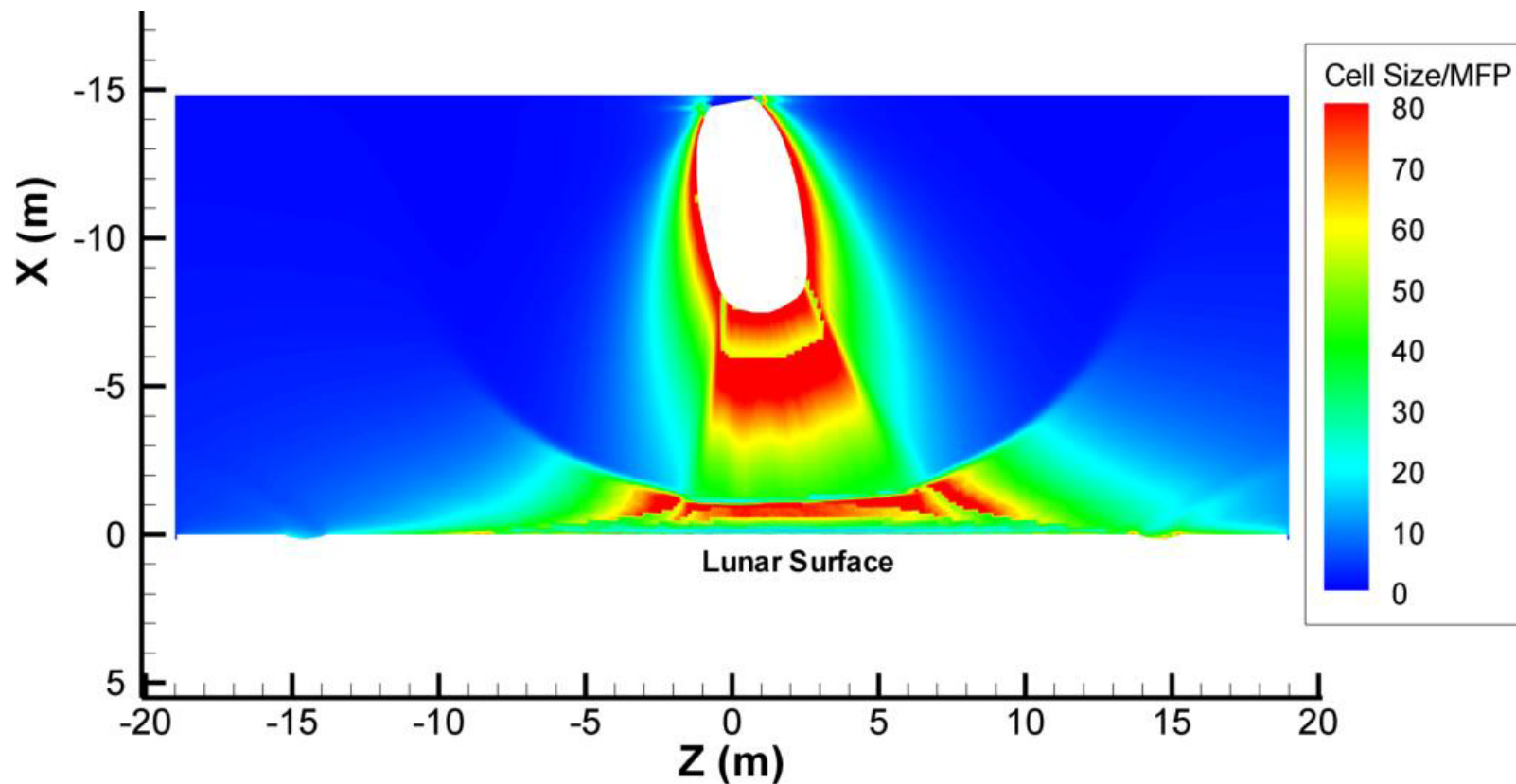
Difficulties during lunar surface plume impingement studies



- Despite the advanced techniques have been incorporated in NASA's DSMC Analysis Code (DAC) to ease requirement on mean free path resolution, current simulations show some simulation artifacts.
 - DAC obtains good results with simulation cell length scales of 4-8 mean free paths.
 - However, in order to simulate Apollo LM lunar impingement with available computational resources length scales on the order of 75-100 mean free paths were needed.
 - Simulations were still very expensive (~100 wall clock hours on 30 processors/case) and required between 100 & 300 million molecules.
- Accuracy of results is mixed:
 - Gross flow field features (e.g. shock location, surface impingement pressure) captured adequately.
 - Finer details, such as the surface shear, show obvious unphysical features such as jumps at locations where grid resolution changes.

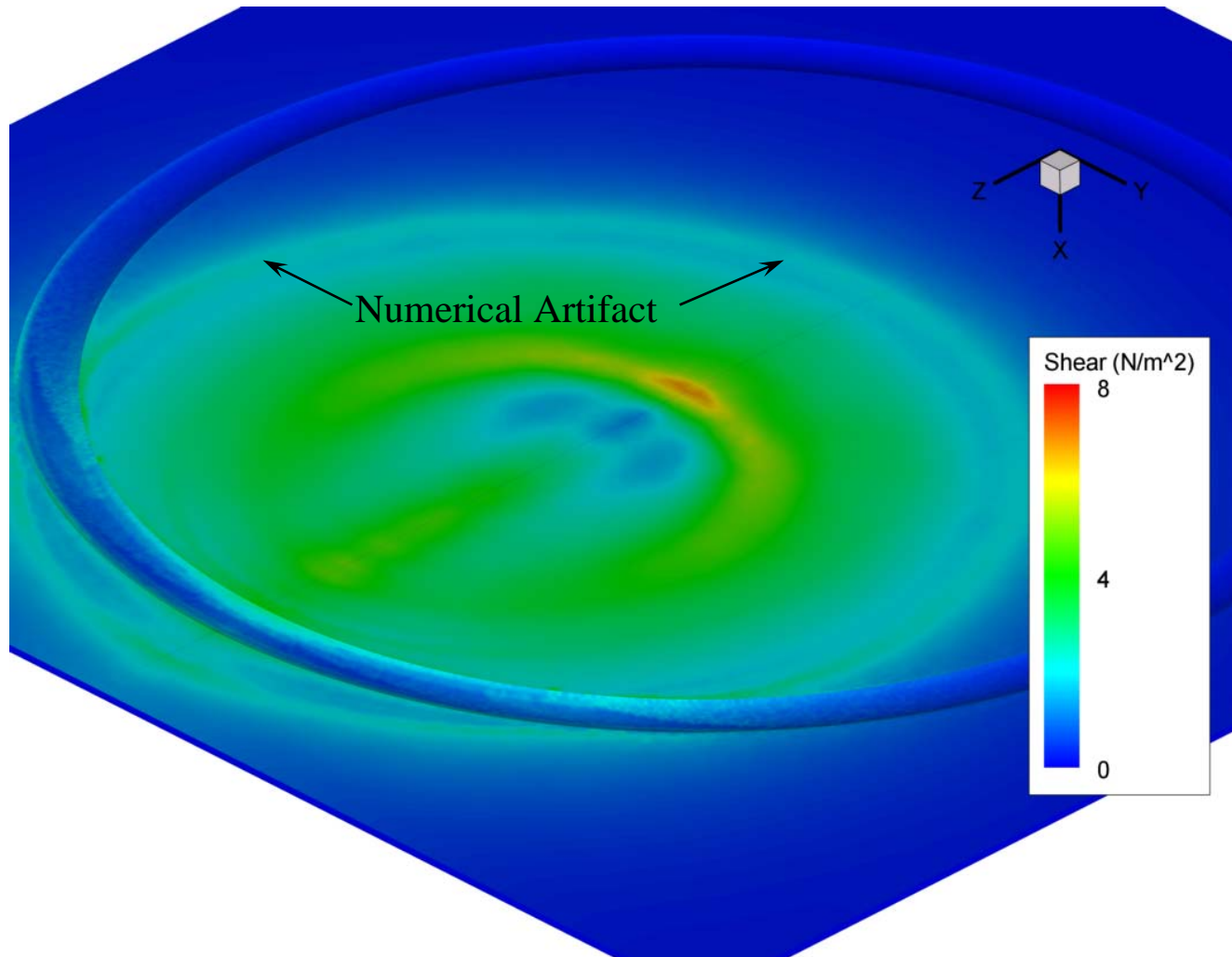


Typical cell resolution for lunar plume impingement analysis





Impingement of Apollo LM Descent Plume on Lunar Surface – Surface Shear





Conclusions & Future Work



- Capability to simulate the lunar surface plume impingement flow environment is possible yet limited.
 - Gross flow features can be captured but finer features have obvious but un-quantified errors.
- Future Work
 - Quantify the error
 - Perform axially symmetric simulation and compare to corresponding simulation run in three dimensions (such as the torroidal crater case with normal plume impingement).
 - DAC (DSMC Analysis Code) performance and accuracy improvements for simulating higher density flows.
 - Increase portion of flow domain which can be treated with CFD.
 - Attempt to include all or portions current DSMC region in the CFD region.
 - Develop improved techniques for handling vacuum boundary condition with CFD tools.
 - Evaluate other CFD tools beyond currently used tools for applicability to lunar plume impingement simulation.